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TECHNICAL REPORT ARCCB-TR-91025

MACHINERY CONDITION SURVEILLANCE SYSTEM

R. K. WHARTON

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US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
CLOSE COMBAT ARMAMENTS CENTER
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Machine Tools	Production Uptime	Early Warning
Mechanical Malfunctions	Non-Cutting (Free-State)	Maintenance
Continuous Monitoring	Dynamic Metal Removal	Multiparameter
Candidate Machining Center	Defective Machinery Components	
Machinery Condition	Integrated System	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Machine tools under heavy production demands are likely candidates to experience mechanical malfunctions such as spindle imbalance, worn shafts and bearings, inadequate/degraded cutting tool coolant, and gearbox overheating. Similarly, it is not uncommon to find moderate vibration levels present in machining processes contributing to dimensional/surface finish inferiority. These conditions result in lost manufacturing time and the attendant expense.

(CONT'D ON REVERSE)

20. ABSTRACT (CONT'D)

A pilot program was instituted offering continuous monitoring of a three-axis machining center. A Machinery Condition Surveillance System (MCSS) measures and analyzes multiparameter signals generated from non-cutting (free-state) and dynamic metal removal activity.

The MCSS is comprised of three dedicated subsystem units: a signal processor, an engineering analysis computer, and a DNC DEC/VAX computer. The integrated system performs automatic collection, processing, and storage of data, and various analysis functions. Using statistical methods yields early warning identification and alert for defective machinery components.

The system assists management is better maintenance scheduling for the machining center, thus contributing to production uptime.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

BACKGROUND AND INTRODUCTION

All machine tools generate mechanical vibrations which contain information about the overall performance of machinery. Facts concealed in time-varying signals are uncovered by evaluation of vibration signal amplitudes over frequency ranges that are generated during operation of the apparatus. Major oscillations can be traced to specific internal component sources of excitation.

Fiscal year 1982 ManTech project, "Machine Tool Dynamic Measurements and Diagnostic System," completed in 1987 (ref 1), showed the feasibility of applying real-time analysis to resolve mechanical problems with machine tools. During the course of this program, the system was also used to determine the causes for poor surface finishes occurring during metal removal processes. The technology and test procedures were adopted by the Maintenance Branch of Watervliet Arsenal's Operations Directorate. The fiscal year 1985 project is a follow-on effort expanding the technology developed from the fiscal year 1982 project.

STATEMENT OF THE PROBLEM

Provisions did not exist for on-line monitoring of machine tool dynamics. Without timely notification of potential mechanical malfunctions such as spindle imbalance, worn shafts and bearings, inadequate and/or degraded cutting tool coolant, and gearbox overheating, catastrophic failure of the machine tool can occur.

APPROACH TO THE PROBLEM

Based on results of the earlier ManTech project (ref 1), a pilot program was initiated to provide continuous surveillance for a three-axis machining center. This pilot program involved the investigation and characterization of several variables that are common to dynamic machine tool operations.

The continuous monitoring technique selected utilizes integrated collection, storage, retrieval, and analyses of multiparameter measurement data obtained from both non-machining (free-state) and dynamic metal cutting (under-load) activity. "Raw" analog data can be analyzed by means of analog-to-digital conversion, fast Fourier transforms, and statistical methods. Suspect defective machinery components and/or conditions can be identified based on analysis of such variables as vibration, coolant flow, temperature, current, and spindle speed. The Machinery Condition Surveillance System (MCSS) generates performance plots depicting possible trends and management reports describing current "health" of the machine tool (Figure 1).

RESULTS

This project resulted in the design, specification, and procurement of an on-line machine tool monitoring system. The various facets of this system are described below.

System Design

The system is comprised of three subsystem units: a signal processor, an engineering analysis computer, and a DNC DEC/VAX information processing computer assigned to perform dedicated tasks. See Figures 2 and 3.

Signal Processor

The signal processor is directly connected to the candidate machining center. The unit is comprised of a microprocessor, monitor, and peripheral equipment, and performs the following functions:

1. Signal conditioning of sensors
2. Analog-to-digital signal conversion
3. Spectral analysis (fast Fourier transform)
4. Engineering unit conversion
5. Frequency peak picking and identification
6. Speed correction of frequencies
7. Determination of significant changes in data
8. Warning and alarm level checking
9. Communications with engineering analysis computer

Engineering Analysis Computer

This computer and ancillary equipment are located in the Maintenance Branch of Watervliet Arsenal's Operations Directorate. A vibration analysis technician has the responsibility for operating and maintaining the system. The unit performs the following functions:

1. Establishes communications with signal processor

2. Modifies MCSS system configuration warning/alarm levels and significant change levels and identifies vibration frequencies

3. Generates plots of current vibration spectra versus g (32.16 ft/sec^2) levels

4. Generates cumulative trend plots, for example, vibration versus time

5. Generates trend plots of machine tools' "health" performance based on predictive statistical analysis of parameters

6. Generates management reports for quick notification of impending failure and/or escalating problems with internal machinery components

DNC DEC/VAX Computer (Information Processing Computer)

The DNC DEC/VAX computer serves as a repository for multiparameter data. During processing of measurements, the engineering analysis computer initiates bidirectional flow of data files from the VAX.

Communications

The communications link connecting all units of the MCSS utilizes a standard telephone modem hookup. The capability for tie-in to a Local Area Network (LAN) Ethernet is available.

Application

A three-axis Giddings & Lewis, Model 10HS, machining center (Figure 4) was selected as the candidate for testing. Figures 5 and 6 show the instrumented machine tool components which are also listed below with the respective condition/status to be monitored.

Internal Components - Parameter/Status

1. Spindle, spindle motor, gearbox - vibration
   a. Condition of bearing, gears, and motor
   b. Initiation of cutting activity

2. Spindle motor - current
   a. Condition of motor
   b. Spindle motor speed
   c. Reference point - component rotation speeds

3. Gearbox - oil temperature
   a. Condition of the oil and the gearbox

4. Z-axis motor - current
   a. Magnitude of load and force for Z-axis motor

5. Coolant - flow rate
   a. Adequacy of lubrication for cutting tools

The machining center was operated on three speed ranges. A choice of speed range 1, BC gear mesh (engaged) was chosen from the various AB, BC, CD, and DE combinations in Figure 7 and Appendix A for discussing the results from analog data.

The complex nature associated with multiparameter analyses required extensive planning. Following are some of the measurement and machining process considerations that were investigated:

1. Parts typically fabricated and cutting tools utilized

2. Listing of cutting tools by number and function, i.e., percent feed, percent rpm, average machining time, and percent minutes

3. Data including number of operational functions to be performed, i.e., signal conditioning and filtering of extraneous information

4. Identification of timing sequences for capture of "raw " data

5. Analog signal levels:

   * Machining states: free-state ("cutting of air") and under-load (machining of metal)

   * Signal levels - the occurrence of insignificant changes

   * Dynamic response of cutting tools for type of material machined, i.e., 4340

   * Cutting tools - number of flutes for each of the three cutters

6. Gears including mechanical problems encountered throughout the monitoring process

Test Procedure

Early in the program, the volume of measurement cutting data generated and analyzed proved to be marginal in value. Reduction of "raw" data without sacrifice to a reliable database was accomplished. Selective measurements produced by three cutting tools commonly used in all machining operations were subsequently processed.

The tool holders for each of the three selected tools were machined and grooved for engaging designated microswitches installed to activate the capture of signal data by the microprocessor.

DISCUSSION OF RESULTS

Analysis of the data proved to be challenging. Two factors affected validity and utilization of processed "raw" measurements. The candidate machining center required evaluation of its dynamic performance behavior while subjected to both free-state (cutting air) and metal cutting activity. The need for this discrimination was to separate machinery from process-related problems. For example, in the case of excessive vibration, a problem could originate from either a dull cutting tool or the presence of excessive wear on a gear or roller bearing assembly. Similarly, data were obtained and characterized for the remaining variables of spindle motor current, cutting tool coolant flow, gearbox oil temperature, and z-axis motor current.

Measurement Variable - Correlation Options

The variables measured and analyzed can often serve by themselves as indicators of impending problems. However, comparison of results obtained from analyses of all parameters offers the best inference and prediction capabilities.

The list below represents graphs that were generated from measurements:

1. Spindle motor speed versus time

2. Spindle motor current versus speed

3. Spindle motor current versus time

4. Z-axis drive motor current versus time

5. Oil temperature versus time

6. Cutting coolant flow versus time

7. Gearbox vibration (peak) versus time

8. Gearbox vibration (peak) versus spindle motor speed

9. Gearbox vibration versus frequency

10. Gearbox vibration (peak) (warning) versus time

11. Spindle motor vibration versus frequency

12. Gearbox vibration versus frequency

13. Gearbox vibration (peak) versus time - 2-inch end mill

14. Gearbox vibration versus frequency - 2-inch end mill

Operational Results

Discussions of curve plots (Figures 8 through 13) are intended to reflect on some very basic efforts undertaken and subsequent interpretations. The analog data were randomly selected from one set of measurement data obtained early in the program.

Free-State (Cutting Air)

Figures 8a and 8b show the daily fluctuations of spindle motor speed and current over a one-week period. Typical machine running responses reveal that increases/decreases in current produce corresponding changes in speed.

Figure 9a is a crossplot of spindle motor current versus spindle motor speed. This figure confirms notable speed increases as current is increased when comparing the cluster of data points at approximately 1900 rpm and 3350 rpm, respectively. In Figure 9b the gear mesh frequency range of 525 to 587.5 Hz offers another crossplot of vibration versus spindle rpm. The peak (g level) clusters vary similarly with motor speed as noted at 1900 and 3350 rpm, respectively. The increase in vibration is caused by increases in motor speed which produce corresponding increases in gear loading forces.

In Figures 10a and 10b, the vibration spectra were obtained from two sets of running speed data, 3314 and 1886 rpm, respectively. In these cases, the vibration level changed by a factor of approximately 3, i.e., 0.008 g versus 0.020 g at approximately 1000 Hz. The changes in vibration level that occurred in these gear mesh frequency plots clearly point out the importance of the MCSS automatic frequency tracking feature for analyzing extremely complicated vibration spectra.

Figure 11 shows variations of BC gear mesh fundamental frequencies (Appendix A) produced over a seven-day period. It is important to note that when in the machining center's free-state, the level varied between 0.003 g and 0.026 g. After examining the spread, a warning level of 0.020 g was programmed as an arbitrary threshold to identify when the signal was high but not considered a threat. An additional upper alarm level warning would be programmed to warn of impending machinery failure.

In Figures 12a and 12b, additional parameters were monitored and can serve as operational "health" indicators or as factors in the various vibration data that were obtained. In this instance, there is no apparent correlation between oil temperature and coolant flow. In Figure 12a, changes in the ambient room temperature, together with the cycling of oil throughout the machinery lubricant, can account for some of the variations observed. In viewing the cutting coolant flow in Figure 12b, daily changes in the flow rate could be attributed to some manual operator intervention to regulate the flow for impending workpiece machining requirements. Significantly, these plots show that variations are normal and should be expected.

Metal Cutting

In Figures 13a and 13b, a 2-inch end mill performs dynamic cutting of metal. For the same one-week period mentioned above, the trend plots show that load and speed are in closer control than in the "free-state" (Figure 11). This is evidenced by the lesser variations in the overall peak vibration amplitude levels over the seven-day period. Under "load" (Figure 13a), the range of g level value is 0.005 versus 0.023. Likewise, in the plot of vibration versus frequency (Figure 13b), the overall level of vibration is lower throughout the entire frequency range.

CONCLUSION

This pilot project has successfully demonstrated continuous automatic machinery surveillance. The techniques applied have provided insight into the requirements and complexities associated with separating measurement data obtained from both free-state "cutting of air" and dynamic metal cutting. Additionally, lessons learned stress that the volume of measurement data to be obtained and analyzed must be limited to its quality and value.

The use of automatic on-line monitoring over direct portable field measurement have greatly enhanced management's ability to acquire information in a timely fashion, while being able to foresee impending machine tool problems.

EPILOG

Implementation

The MCSS has been accepted by Benet Laboratories. After the pilot system on the candidate machining center demonstrated satisfactorily, the system was implemented and transferred to the Operations Directorate of Watervliet Arsenal. Presently, archiving of multiparameter measurements from various machining operations is underway. The system's capability for predicting failure shall be derived from an expanded database. "Fine tuning" of the system's early warning diagnostics is being conducted by the Maintenance Branch end user activity. The expansion potential for the single pilot system offers surveillance coverage for up to four additional machining centers.

Regarding full plant coverage, the variety of diverse machine tool applications requires further investigation concerning use of the centralized DEC/VAX, LAN Ethernet, timesharing, and more personnel trained to operate and maintain a large machine tool surveillance system.

Rapidly changing manufacturing technology in this area mandates formation of an advisory group to plan short and long-term machinery monitoring needs. The tapping of additional sources of information to be derived from the database for planning strategies will also need to be investigated.

Benefits

The following benefits will be derived from the utilization of on-line machinery surveillance:

1. Detection of incipient machine component wear/failure

2. Discovery of escalating machinery deterioration before destruction is imminent

3. Adoption of scheduled maintenance activity

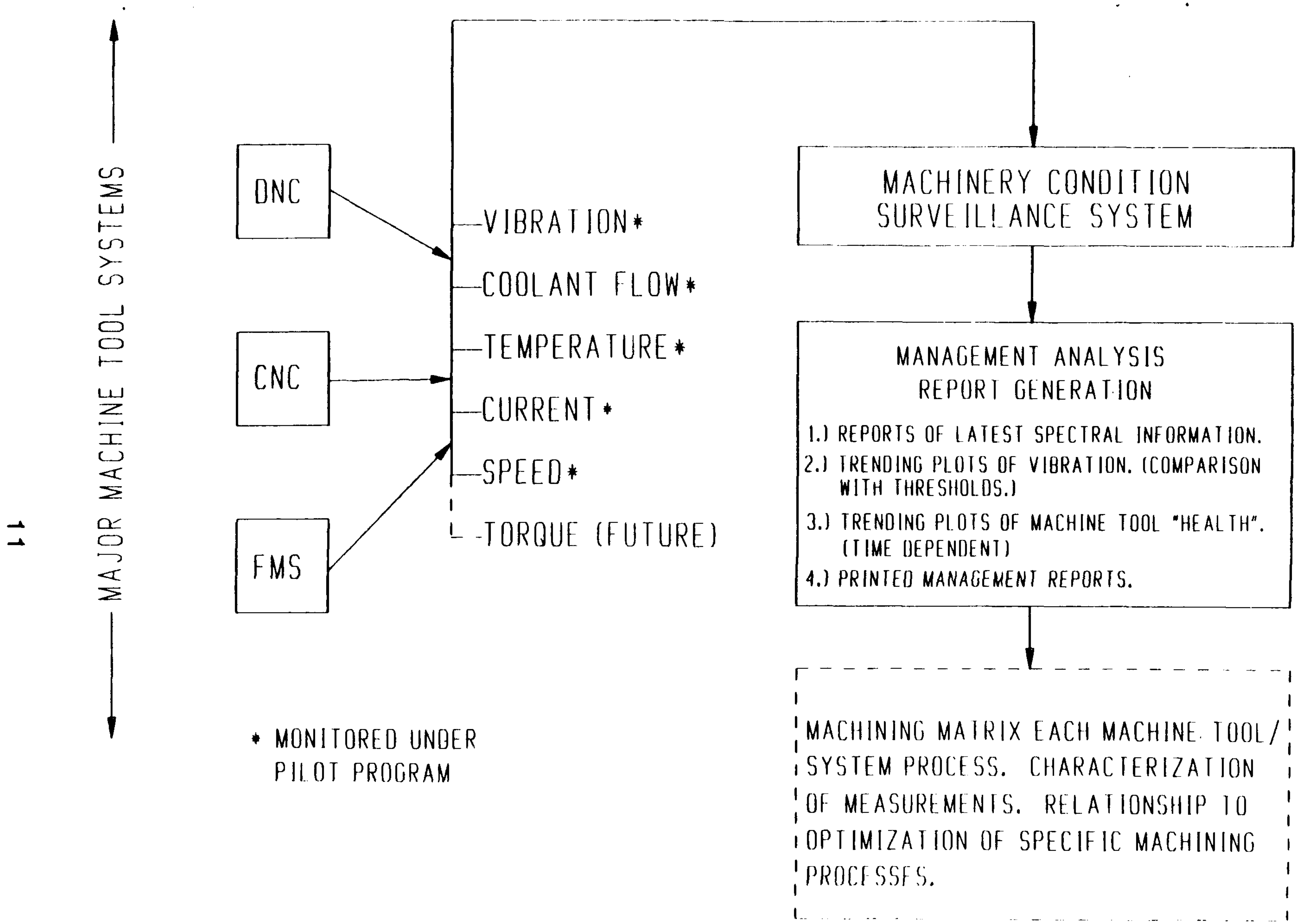
4. Improvement of quality of surface finishes and accuracy of dimensions on weapon components

5. Reduction of unscheduled machine tool downtime and associated production stoppage

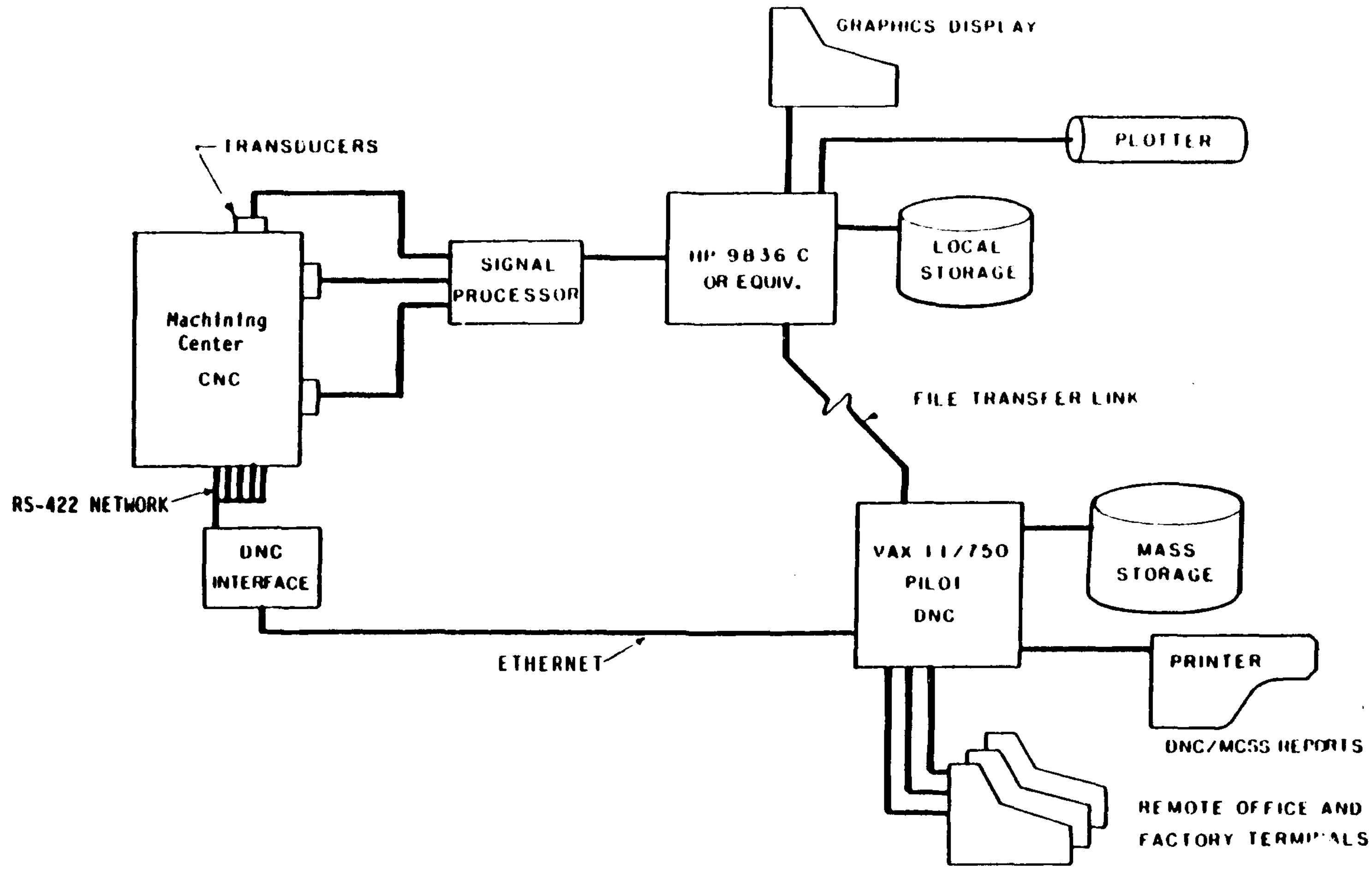
6. Effective management of production costs

REFERENCE

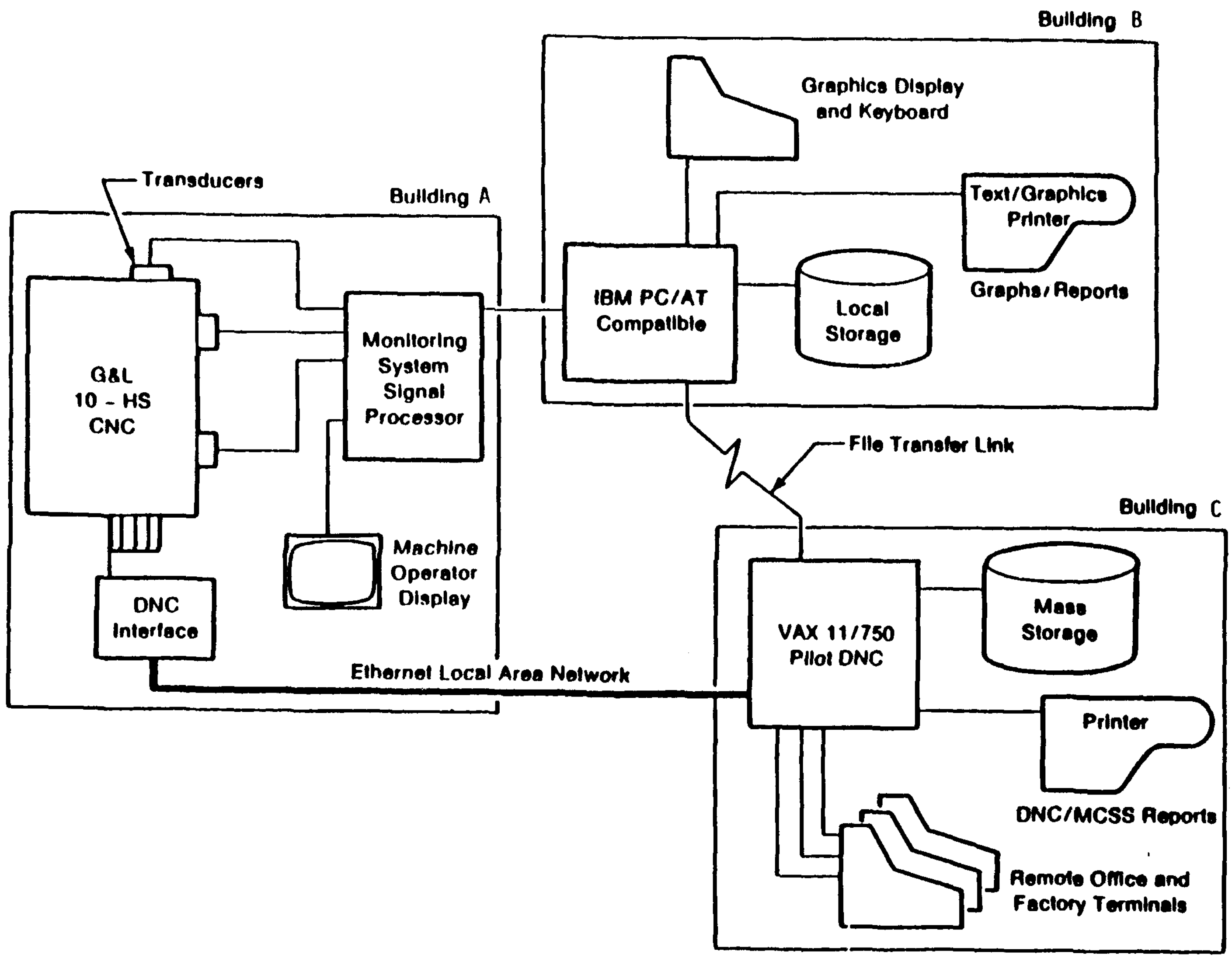
1. R.K. Wharton and T.P. Vincent, "Machine Tool Dynamic Measurements and Diagnostic System," U.S. Army ARDEC Technical Report ARCCB-TR-89001, Benét Laboratories, Watervliet, NY, January 1989.



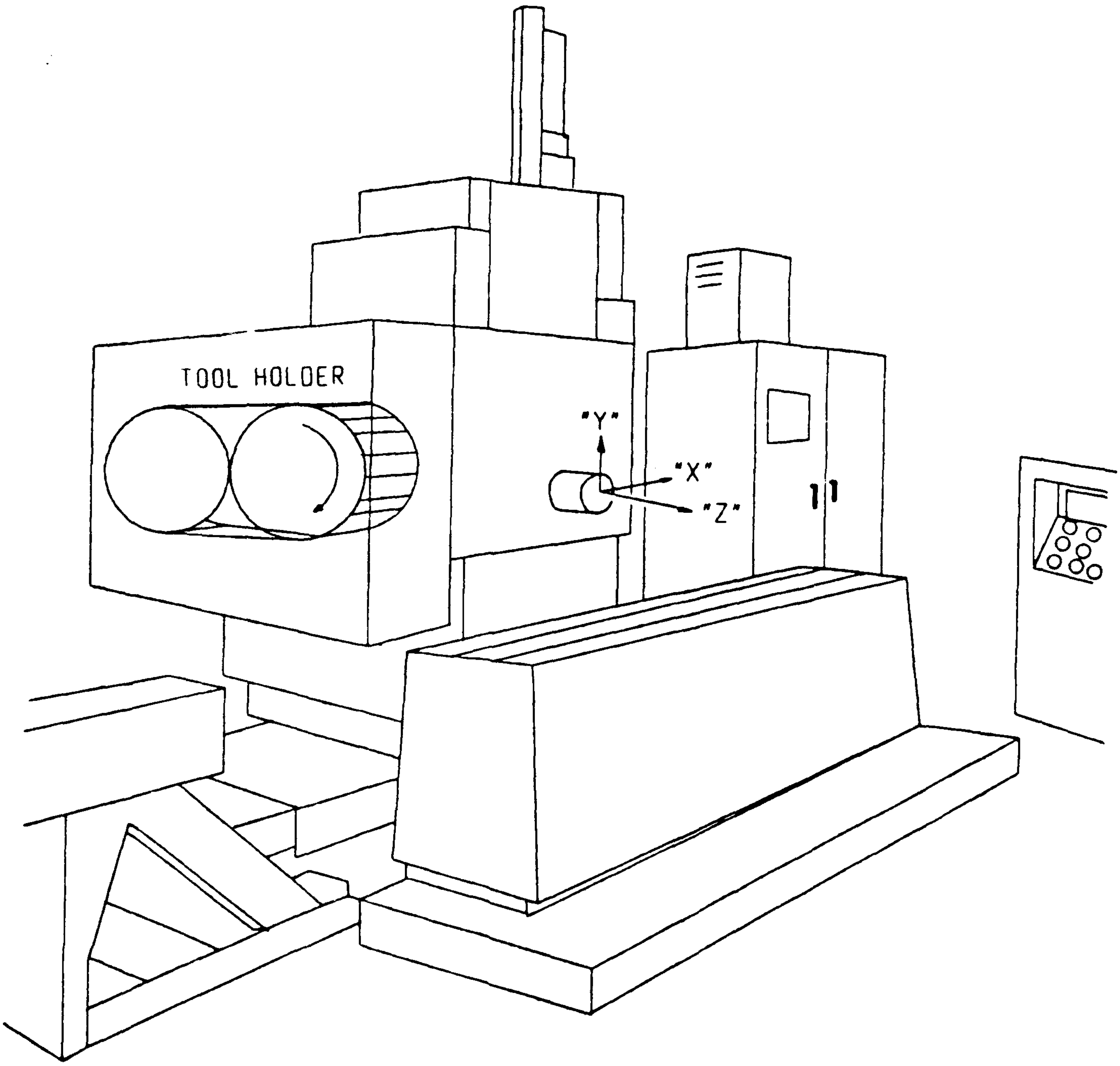
1. Parameter measurement and analysis concept.



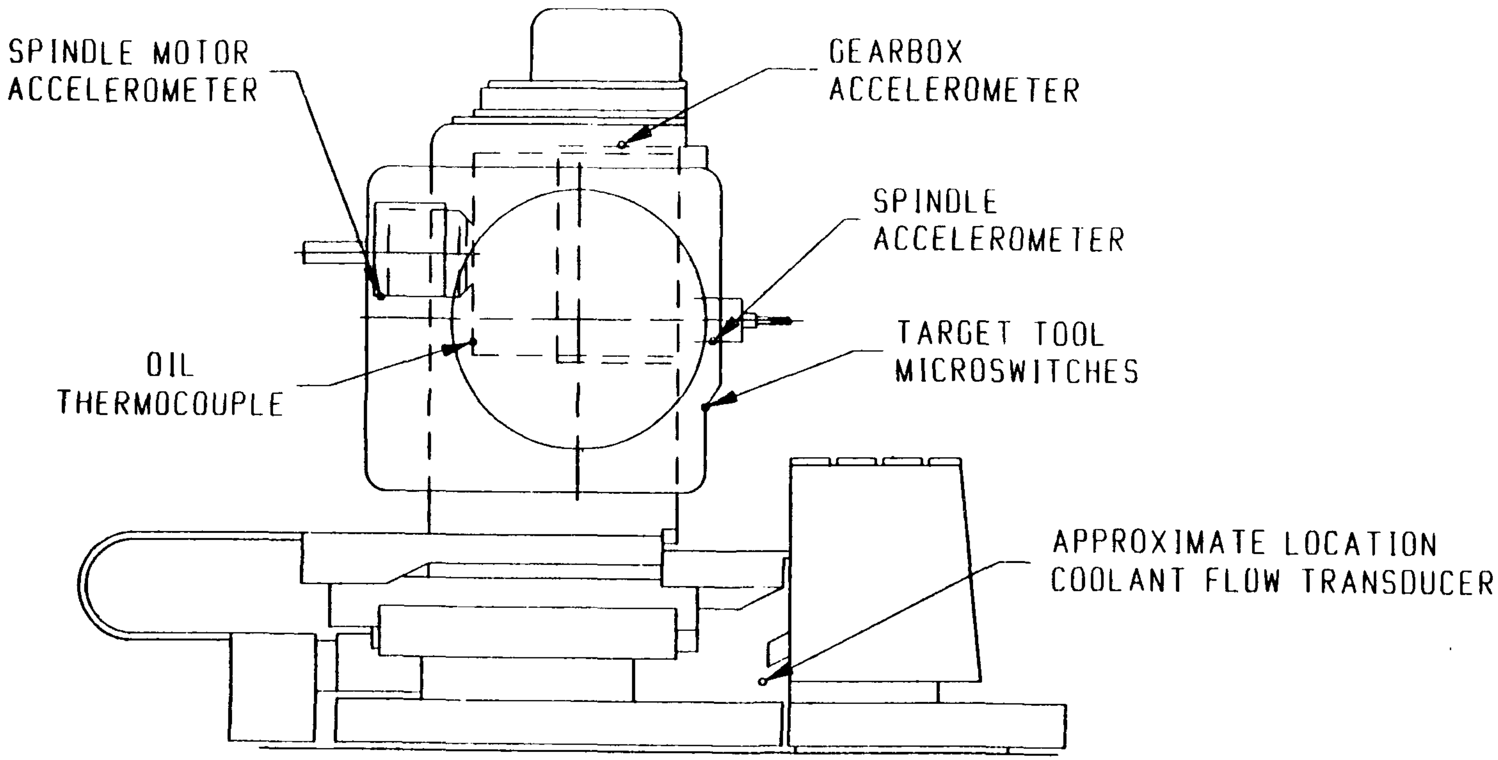
2. MCSS proposed pilot system configuration.



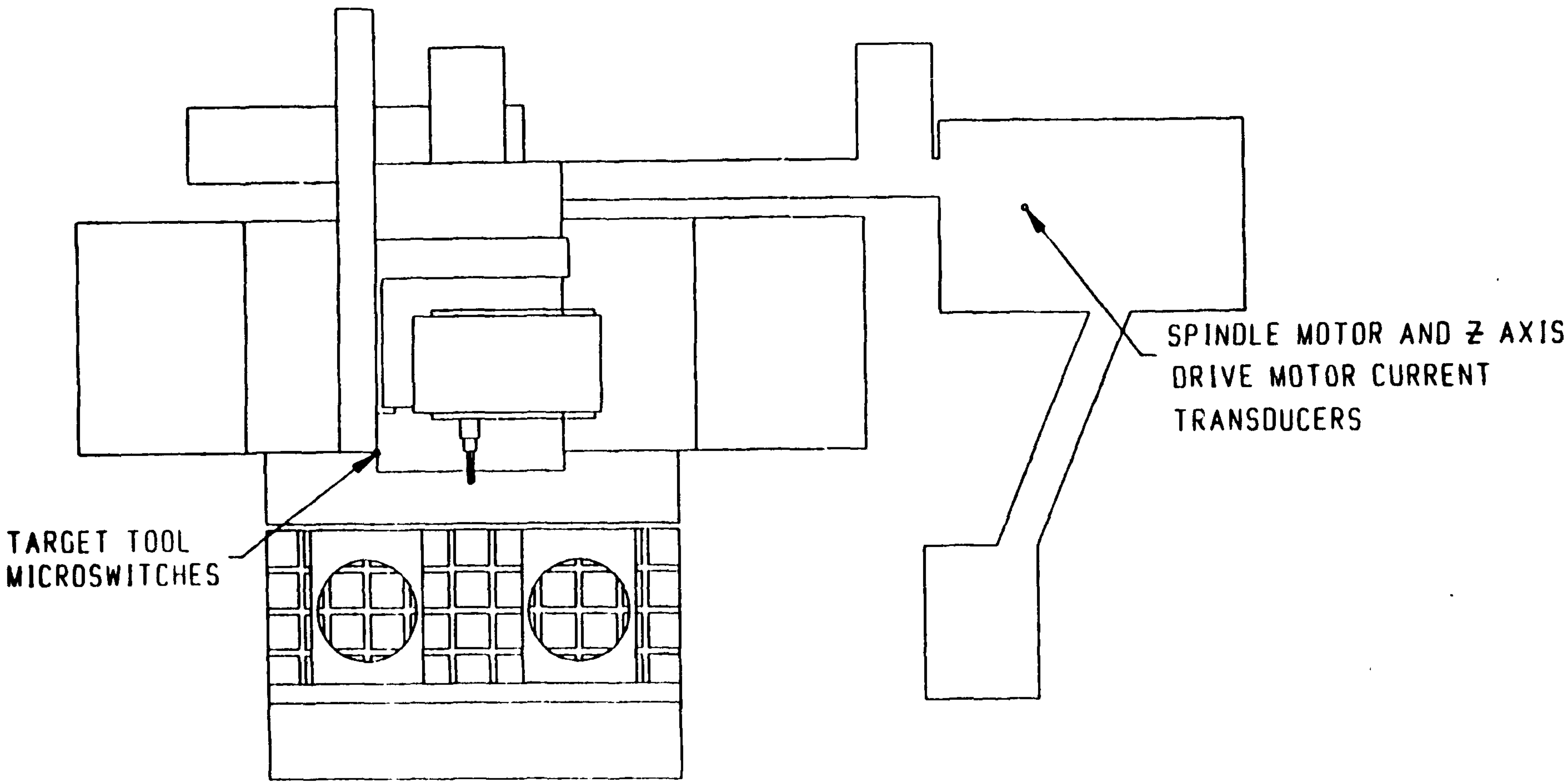
3. MCSS plant layout subsystems.



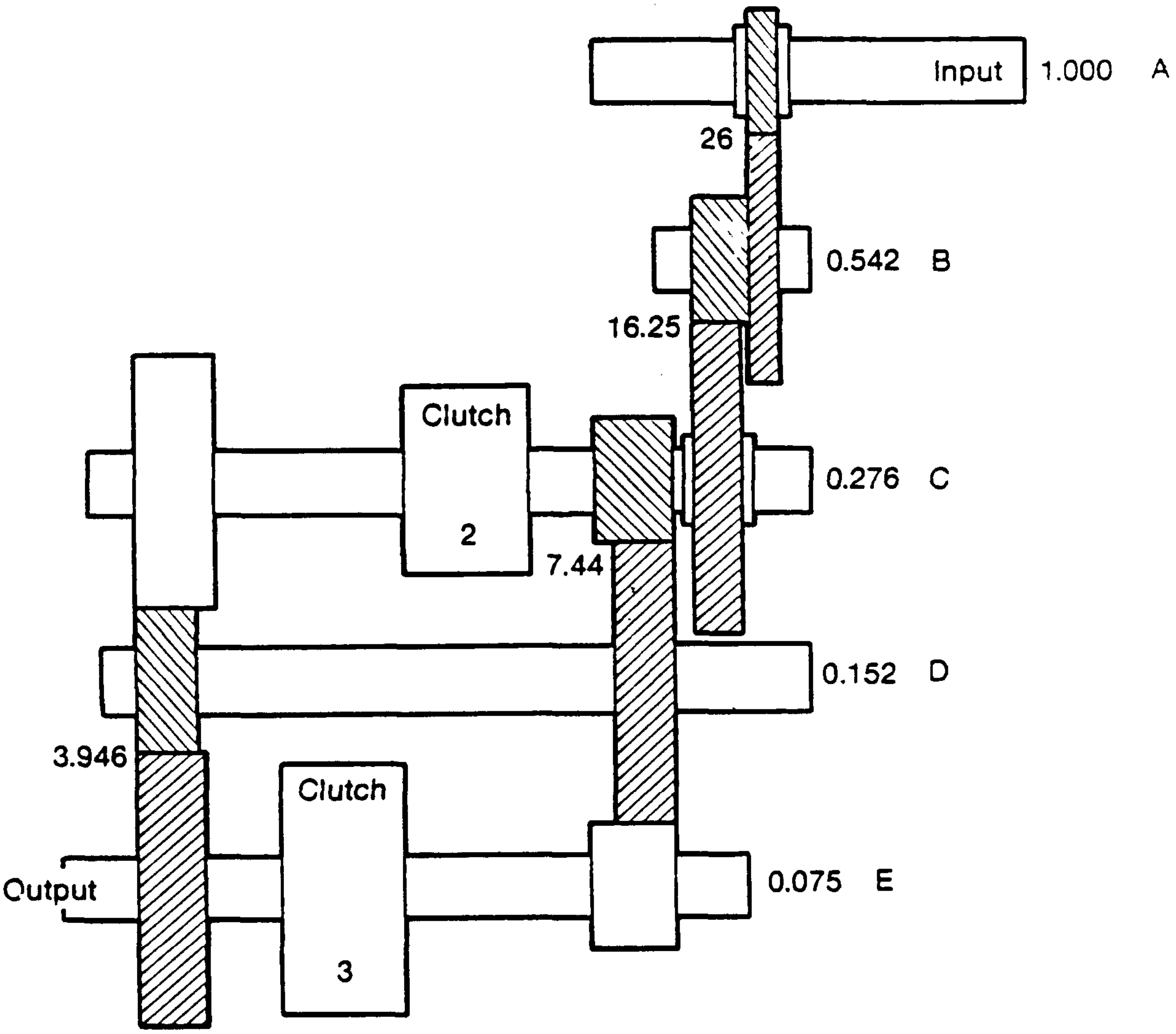
4. Three-axis Giddings & Lewis machining center.



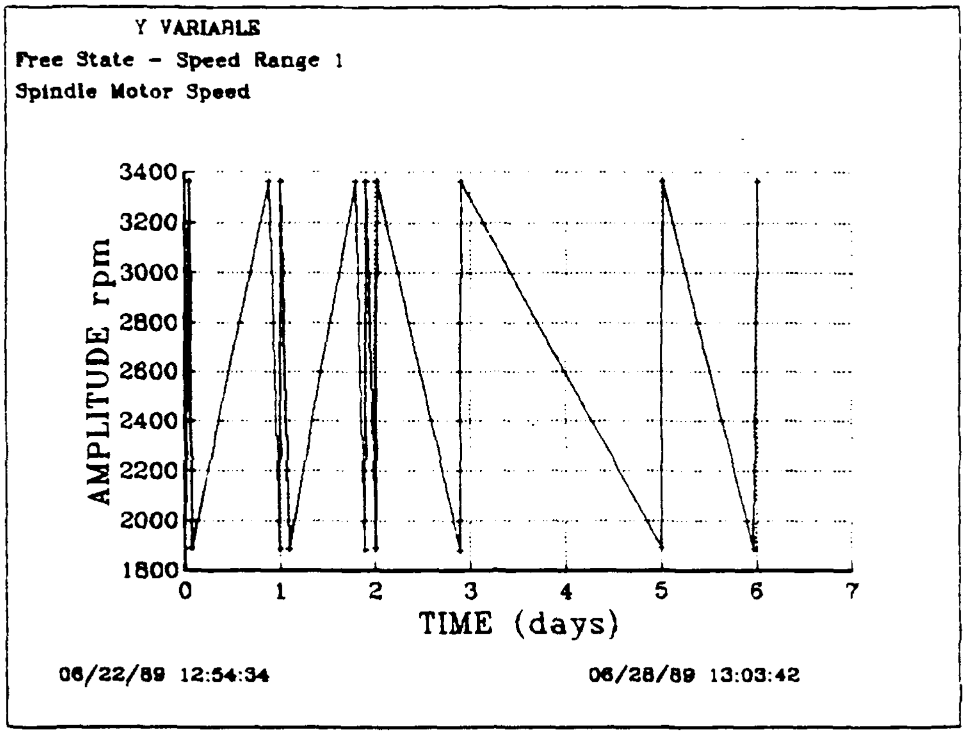
5. Side view of machining center showing transducer locations.



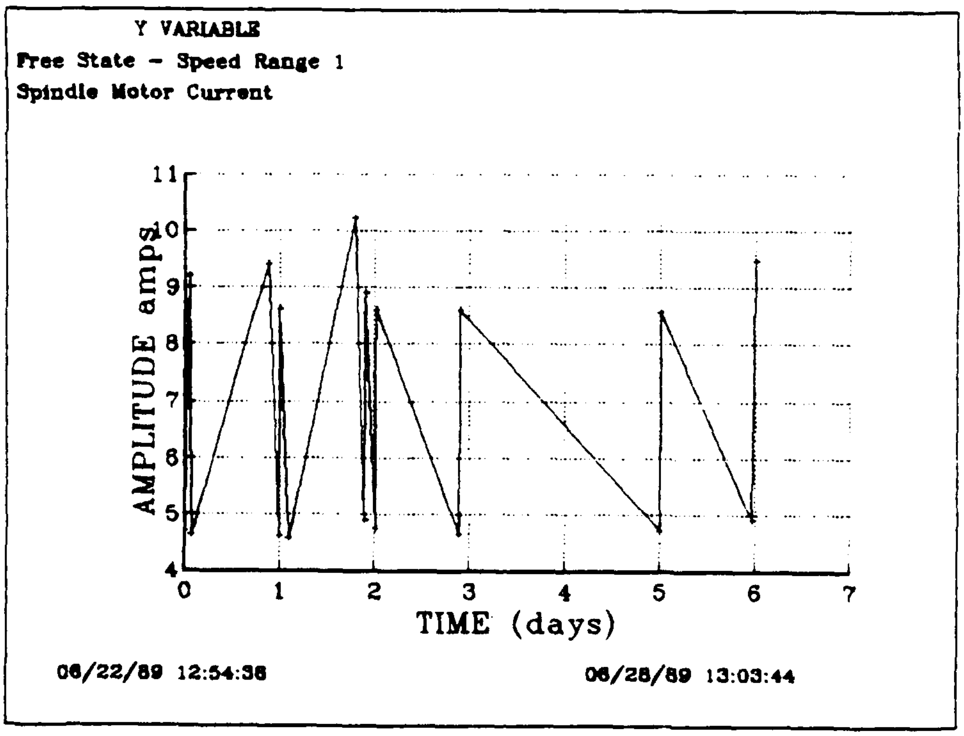
6. **Top view of machining center showing transducer locations.**



7. Rotational frequencies as related to spindle motor speed - speed range I.

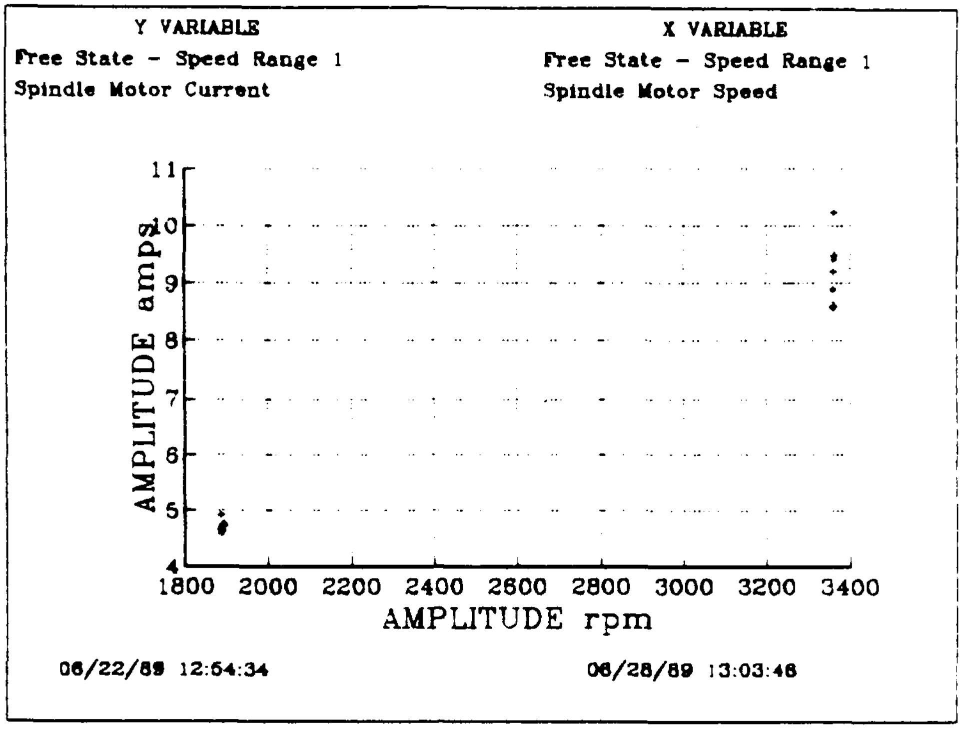


a. **Spindle motor speed versus time.**

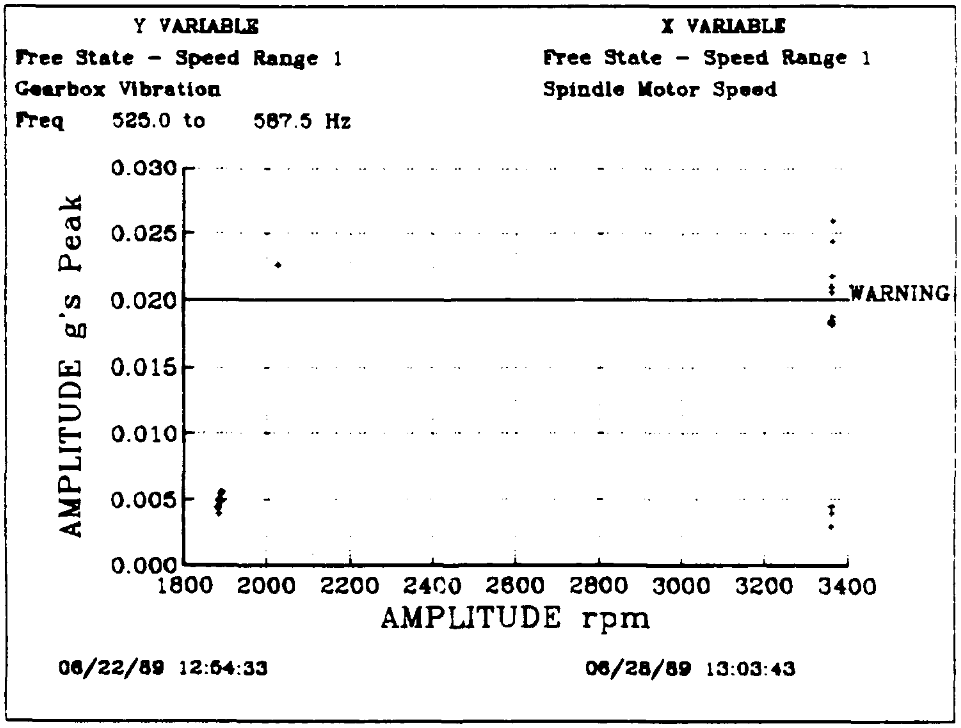


b. **Spindle motor current versus time.**

8. Performance characteristics (free-state).

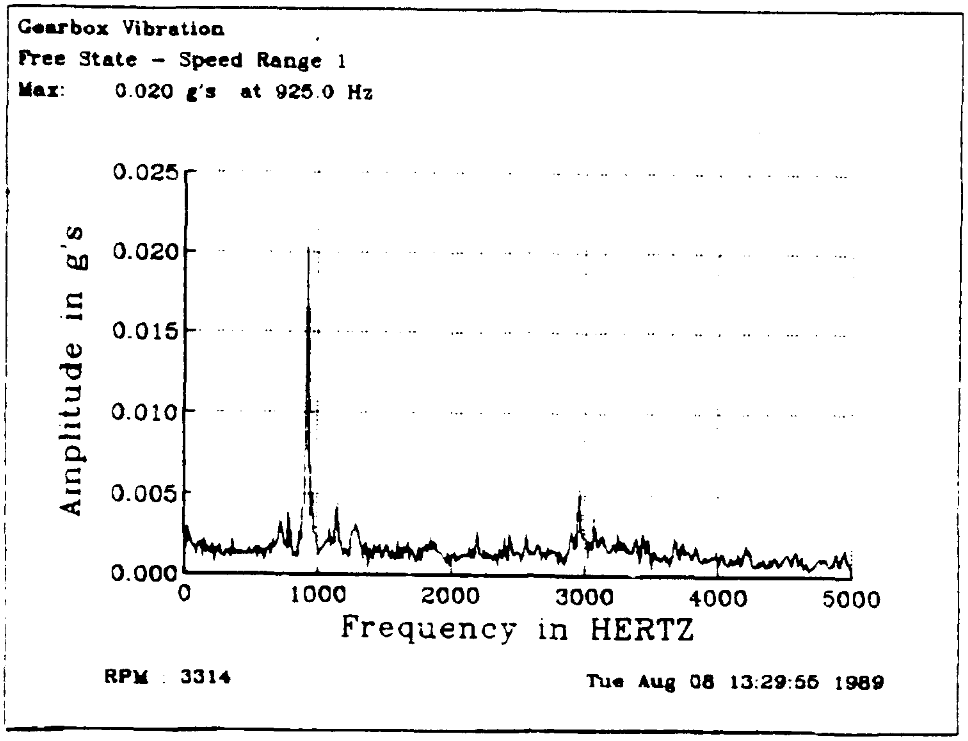


a. Spindle motor current versus spindle motor speed.

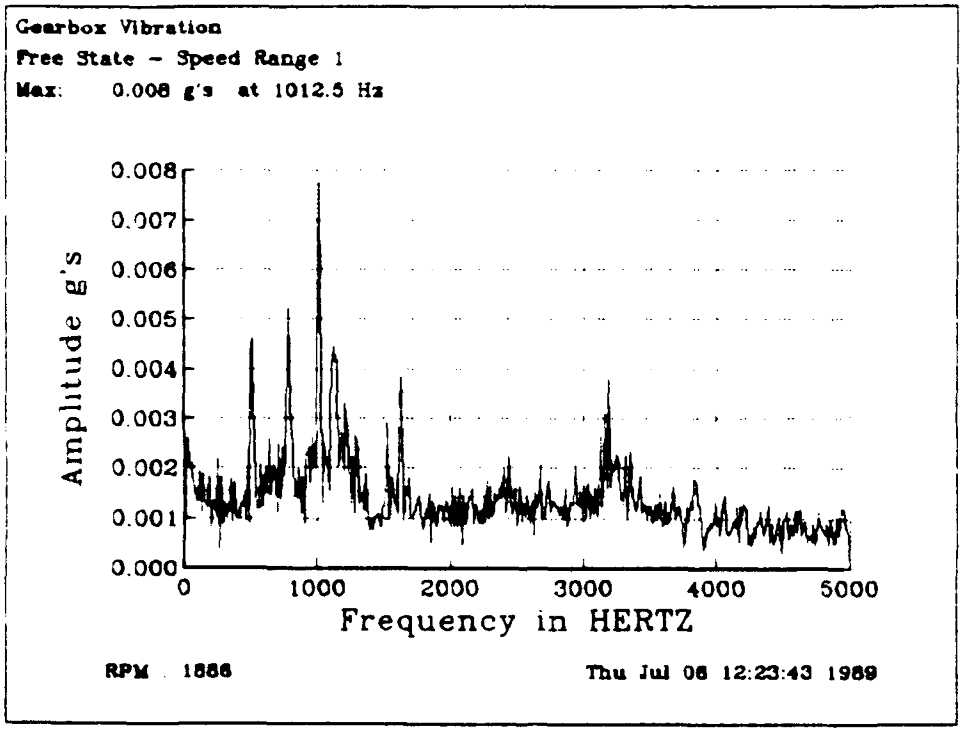


b. Gearbox vibration (peak) versus spindle motor speed.

9. Performance characteristics (free-state).

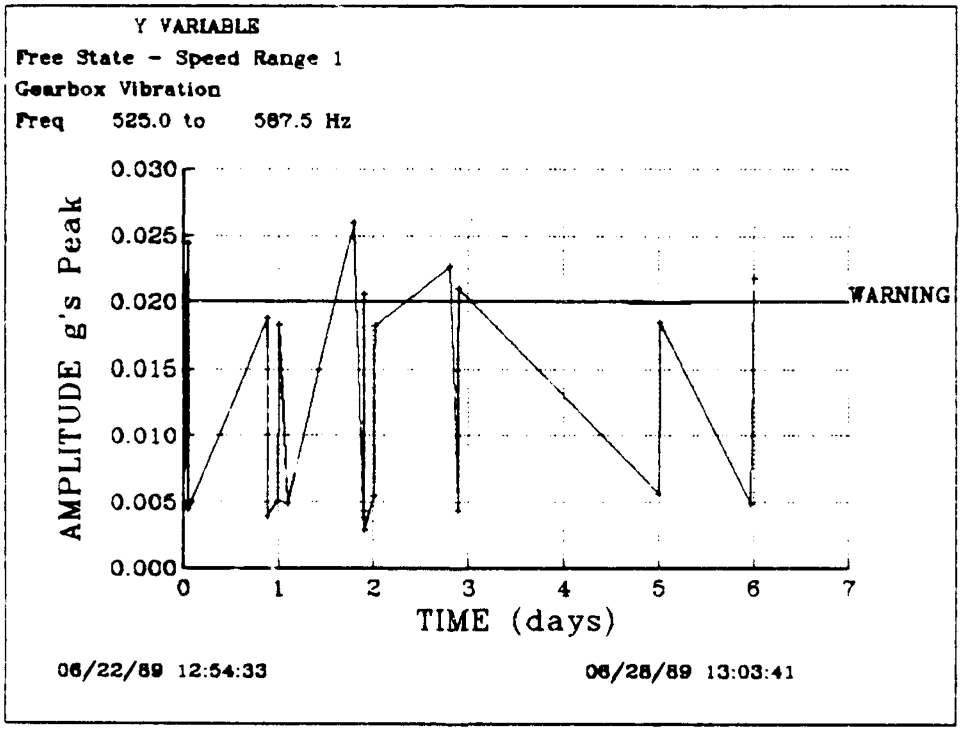


a. **Case 1 - speed of operation at 3314 rpm.**

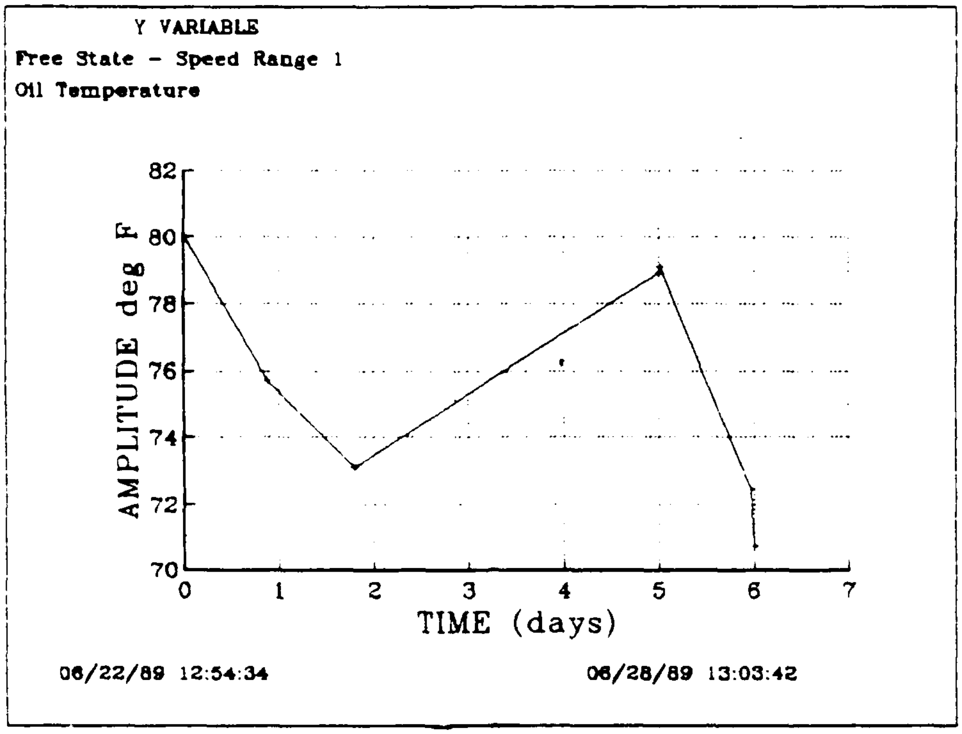


b. **Case 2 - speed of operation at 1886 rpm.**

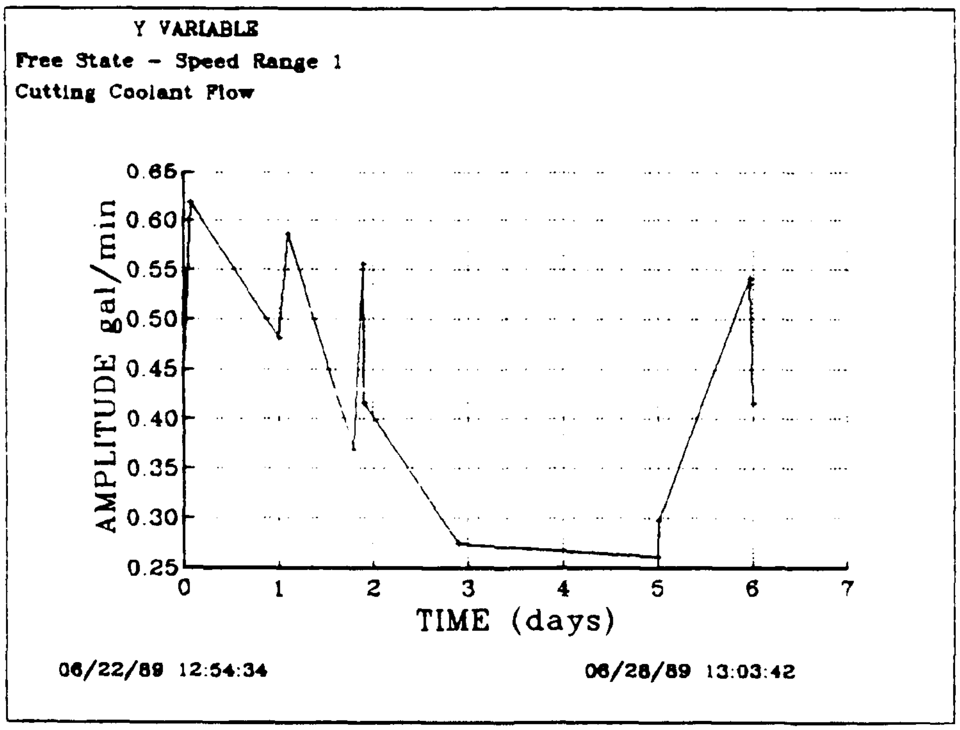
10. Performance characteristics (free-state); gearbox vibration versus frequency.



11. Performance characteristics (free-state); gearbox vibration (peak) versus time.

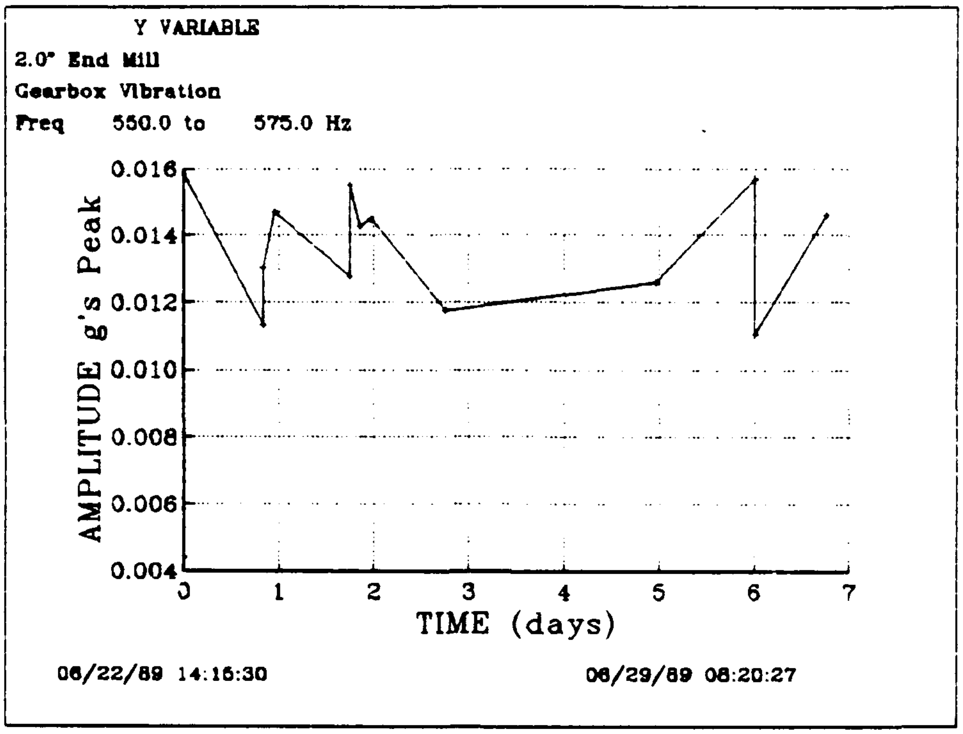


a. Oil temperature versus time.

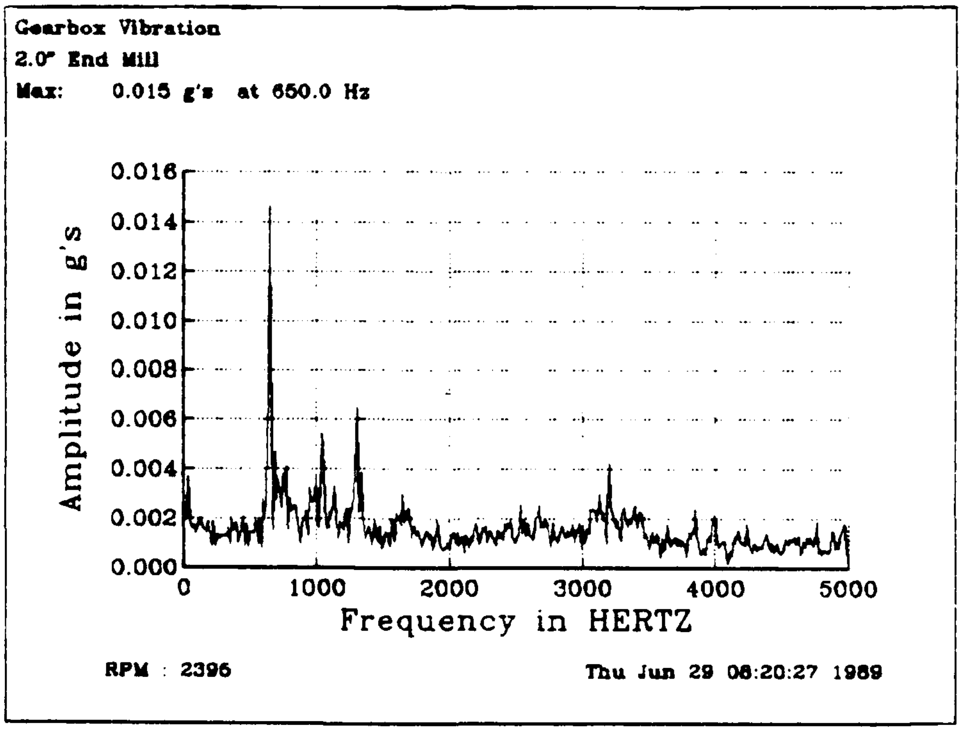


b. Cutting coolant flow versus time.

12. Performance characteristics (free-state).



a. **Gearbox vibration (peak) versus time.**



b. **Gearbox vibration versus frequency - speed of operation at 2395 rpm.**

13. Dynamic response to metal removal activity; 2-inch end mill.

APPENDIX A

CALCULATIONS - SPINDLE ROTATION (RPM) VS. VIBRATION GEAR MESH FREQUENCIES (Hz)

$i := 20 \, .. 50$

$rpm_i := 60 \cdot i$ $ab_i := 26 \cdot i$ $bc_i := 16.25 \cdot i$

$cd_i := 7.44 \cdot i$ $de_i := 3.946 \cdot i$

RANGE ONE

rpm_i	ab_i	bc_i	cd_i	de_i
1200	520	325	148.8	78.92
1260	546	341.25	156.24	82.866
1320	572	357.5	163.68	86.812
1380	598	373.75	171.12	90.758
1440	624	390	178.56	94.704
1500	650	406.25	186	98.65
1560	676	422.5	193.44	102.596
1620	702	438.75	200.88	106.542
1680	728	455	208.32	110.488
1740	754	471.25	215.76	114.434
1800	780	487.5	223.2	118.38
1860	806	503.75	230.64	122.326
1920	832	520	238.08	126.272
1980	858	536.25	245.52	130.218
2040	884	552.5	252.96	134.164
2100	910	568.75	260.4	138.11
2160	936	585	267.84	142.056
2220	962	601.25	275.28	146.002
2280	988	617.5	282.72	149.948
2340	1014	633.75	290.16	153.894
2400	1040	650	297.6	157.84
2460	1066	666.25	305.04	161.786
2520	1092	682.5	312.48	165.732
2580	1118	698.75	319.92	169.678
2640	1144	715	327.36	173.624
2700	1170	731.25	334.8	177.57
2760	1196	747.5	342.24	181.516
2820	1222	763.75	349.68	185.462
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